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Biological carbon capture and utilization (BCCU): An integrated process for O_2 production and reduced CO_2 emission

Captura e utilização biológica de carbono (BCCU): um processo integrado para produção de O2 e emissão reduzida de CO2

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Brazilian Journal of Development

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ABSTRACT

The objective of this work was to evaluate the O_2 production and CO_2 emission in an integrated process. The experiments were performed in a bubble column photobioreactor with a volume of 2 L, luminous intensity of 15 µmol/m^2/s, aeration of 1 VVM with air injection enriched with 15% carbon dioxide. The photobioreactor was integrated into a bio-combustion furnace designed on a laboratory scale, where the emissions were evaluated. The fuel used was petroleum coke. The experimental conditions in the were: initial coke mass 1.0 g, total combustion time of 20 min, and airflow 1.0 L/min. A gas chromatograph to determine greenhouse gas emission was used. The results showed a CO_2 capture and O_2 production in the photobioreactor of 0.46 and 0.40 kg/m³, respectively. Furthermore, the CO_2 emissions in the furnace were 0.71 kg/m³. In this sense, the photobioreactor demonstrated the ability to capture carbon and produce bioproducts, and when integrated into a bio-combustion process, presented the potential to mitigate greenhouse gas.

Keywords: microalgae, photobioreactor, bioproduct, bio-combustion, greenhouse gas, process integration.

RESUMO

O objetivo deste trabalho foi avaliar a produção de O_2 e a emissão de CO_2 em um processo integrado. Os experimentos foram realizados em um fotobiorreator de coluna de bolhas com um volume de 2 L, intensidade luminosa de 15 µmol/m^2/s, aeração de 1 VVM com injeção de ar enriquecido com 15% de dióxido de carbono. O fotobiorreator foi integrado em um forno de bio-combustão projetado em escala laboratorial, onde as emissões foram avaliadas. O combustível usado foi o coque de petróleo. As condições experimentais foram: massa inicial de coque 1,0 g, tempo total de combustão de 20 min e fluxo de ar 1,0 L/min. Um cromatógrafo gasoso foi usado para determinar as emissões do gás de efeito estufa. Os resultados mostraram captura de CO_2 e produção de O_2 no fotobiorreator de 0,46 e 0,40 kg/m³, respectivamente. Além disso, as emissões de CO_2 no forno foram de 0,71 kg/m³. Nesse sentido, o fotobiorreator demonstrou a capacidade de capturar carbono e produzir bioprodutos e, quando integrado a um processo de bio-combustão, apresentou o potencial de mitigação de gases de efeito estufa.

Palavras-chave: microalga, fotobiorreator, bioproduto, bio-combustão, gás de efeito estufa, integração de processo.

Brazilian Journal of Development

1 INTRODUCTION

The impending energy crisis related to the extensive use of fossil resources has caused severe environmental damage, mainly due to carbon dioxide (CO_2) emissions (Kothari et al., 2019). According to the International Energy Agency, global energy needs are expected to increase by 55% by 2030, at a rate of 1.8% per year (IEA, 2020).

Given these estimates, several technologies for carbon capture, utilization, and storage by physical and chemical methods have been suggested to reduce atmospheric levels of CO_2 and other polluting gases (Zhu et al., 2017). However, they have many hurdles in terms of cost and technological maturity.

Among the various options available today, biological carbon capture and utilization (BCCU) has been considered as a potential technological route to treat and reuse industrial gaseous effluents (Severo et al., 2018). The BCCU is mediated by microalgae-based processes, which are developed in photobioreactors. These cultivation systems are designed to obtain double benefit: to achieve an effective CO_2 bioconversion rate and to generate several products of commercial interest. There are many bioproducts with different applications, including nutraceuticals, colorants, food supplements, bioenergy, and biofuels (Andrade et al., 2020).

However, the focus has been on products released in the photobioreactors exhaust gases, such as oxygen (O_2) and volatile organic compounds (VOCs) (Jacob-Lopes et al., 2010). These metabolites have the potential to be integrated into industrial combustion systems to improve the performance of thermal equipment, as demonstrated in Severo et al. (2018). Additionally, considering the sequential study by Severo et al. (2020), it has been shown that the integration of the photobioreactor exhaust gases into a bio-combustion furnace is also a promising approach to reduce fuel consumption and greenhouse gas emissions.

Considering these aspects, the strategy of integrating microalgae processes could be a viable alternative to solve the issues of sustainability and bioeconomy in the face of fossil-based industrial systems (Severo et al., 2019). Although attractive, it is necessary to subject these bioprocesses to an analysis of environmental performance. This is what we propose in this study, which aimed to evaluate the O_2 production and CO_2 emission in an integrated process.

Brazilian Journal of Development

2 MATERIAL AND METHODS

2.1 MICROORGANISM AND CULTURE CONDITIONS

The microalgae used was the *Scenedesmus obliquus* CPCC05, obtained from the Canadian Phycological Culture Centre. Stock cultures were propagated and maintained in synthetic BG-11 medium (Rippka et al., 1979) and pH 7.6. The incubation conditions used were 30°C, the photon flux density of 15 μmol m^{-2} s^{-1}, and a photoperiod of 12 h.

2.2 DESCRIPTION OF THE INTEGRATED BIO-COMBUSTION SYSTEM

2.2.1 Photobioreactor and obtaining the kinetic data

Measurements were made in a bubble column photobioreactor (Maroneze et al., 2016), operating in batch mode, fed with 2 L of culture medium, initial cell concentration of 0.1 g L^{-1}, isothermal reactor operating at a temperature of 26°C, photon flux density of 150 μmol m^{-2} s^{-1} and continuous aeration of 1 VVM (volume of air per volume of culture per minute) with the injection of air enriched with 15% CO_2.

The cell density, CO_2, and O_2 concentrations were monitored every 24 h during the growth phase of the microorganism. The tests were carried out in triplicate. Carbon dioxide and oxygen concentration data were used to calculate the gaseous exchange rates according to the methodology described by Jacob-Lopes et al. (2010).

The determination of the concentrations of CO_2/O_2 of photobioreactor exhaust gases was performed according to Jacob-Lopes & Franco (2013) and Severo et al. (2018).

2.2.2 Bio-Combustion furnace and obtaining the kinetic data

The experiments were carried out in a bio-combustion furnace manufactured in laboratory-scale, according to Severo et al. (2018). The experimental apparatus consisted of a furnace made of stainless-steel plates, with the coating composed of the refractory material to reduce the loss of heat through the walls. The internal dimensions of the combustion chamber were height (H) = 40 cm, depth (D) = 20 cm and width (W) = 20 cm. The furnace was equipped with two 300 W electrical resistors. A ceramic holder was inserted into the central combustion chamber, which was used to introduce the fuel sample. The exhaust gases from the photobioreactor were directed into the chamber through a stainless-steel tube located at the bottom of the furnace, measuring the length (L) = 80 cm and internal diameter (ID) = 3 mm. The gases resulting from combustion were routed through the outlet channel, located at the

top of the chamber. The system features a moisture filter and two pumps to control the flow of gas.

The experiments were monitored every 24 h during the growth phase of the microorganism by the injection of the exhaust gases from the photobioreactor and other oxidants tested in the biofuel furnace. The experimental conditions were as follows: initial coke mass 1.0 g, total combustion time of 20 min, and airflow 1.0 L/min.

2.3 FUEL COMPOSITION

The fuel used in the combustion experiments was petroleum coke. The sample was characterized using a PerkinElmer 2400 CHNS/O elemental analyzer (PerkinElmer, Waltham-MA, USA). For furnace feed, the exhaust gases from the photobioreactor in different times of residence.

2.4 CO_2 DETERMINATIONS IN THE FURNACE OUTPUT

A gas chromatograph (GC) was used to determine the CO_2 emissions experimentally. The equipment used was a GC-2014 Greenhouse Gas Analyzer (Shimadzu, Kyoto, Japan), equipped with six-packed chromatographic columns (Supelco, Bellefonte-PA, USA) connected to the following detectors: thermal conductivity detector (TCD), flame ionization detector (FID), and electron capture detector (ECD). The FID was used for the CO_2 determination. Helium was used as a carrier gas. The gaseous samples at the furnace output were collected in previously evacuated vials; 5 mL of sample was injected using a gastight syringe (Hamilton, Bellefonte-PA, USA). The peak areas obtained using the integrator Software GC solution were compared with reference curves to determine the gas concentration (Severo et al., 2020).

3 RESULTS AND DISCUSSION

Figure 1 shows the dynamics of CO_2 capture rates and O_2 production of *Scenedesmus obliquus* microalgae in the photobioreactor at different cell residence times.

Brazilian Journal of Development

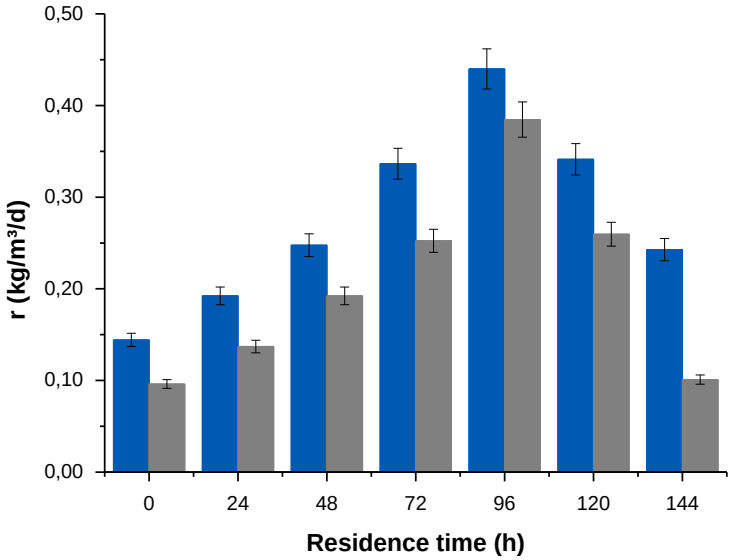

Figure 1. Carbon dioxide capture and oxygen release rates. Note: ■ CO_2 and ■ O_2.

The maximum O_2 production reached was 0.40 ± 0.11 kg/m³ in 96 h of cultivation. For the captured CO_2, the value obtained was 0.46 ± 0.13 kg/m³ at the same residence time. It can be observed that the behavior of both curves is similar throughout the experiment, which demonstrates the direct relationship between consumption versus production rates. According to Jacob-Lopes et al. (2010), this behavior is related to the depletion of nutrients and inorganic carbon in the culture medium associated with the excretion of bioproducts. Among them, they can be generated metabolically O_2, VOCs, and CO_2 unconverted, which could be reused as an oxidizer, gaseous fuels, and nitrogen diluent, respectively, in combustion processes (Jacob-Lopes et al., 2017).

In addition, the photobioreactor exhaust gases were injected into the bio-combustion furnace, and the thermal performance of the system was evaluated, according to the data obtained in Severo et al. (2018). The VOCs presented an energy potential of 86.32 MJ kg^{-1}. From this, CO_2 emissions were analyzed, as shown in Figure 2.

Brazilian Journal of Development

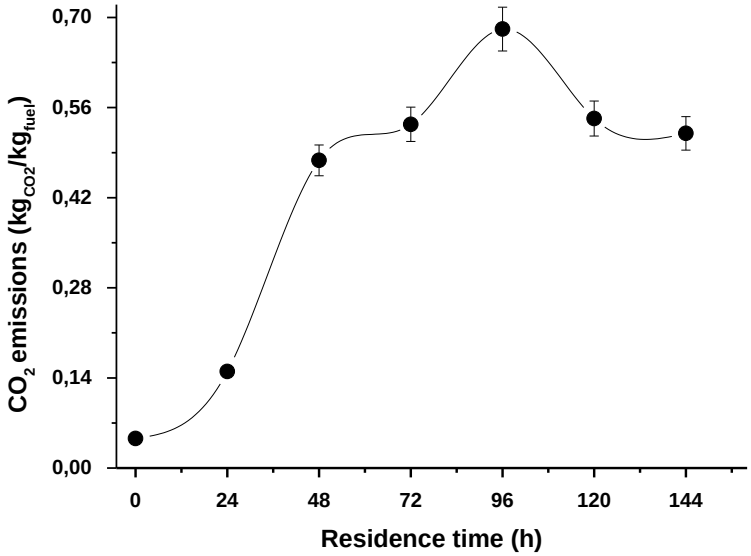

Figure 2. Dynamics of CO_2 emissions in the bio-combustion furnace.

Based on the analysis of the CO_2 emission profile, about 0.71 ± 0.14 kg of CO_2 is emitted for every 1 kg of petroleum coke burned. This value is quite different from the theoretical stoichiometric value, however, which is 3.30 kg_{CO2}/kg_{fuel}, indicating that the bio-combustion system emits 80% less CO_2 than a conventional combustion technology. This may be related to the fact that the amount of CO_2 produced is directly related to the percentage of O_2 injected into the system, which also reflects the reduction of the amount of fuel burned. When considerable O_2 concentrations are enriched in the combustion, there is the volumetric displacement of the N_2 of the air, favoring the heat transfer inside the furnace and, therefore, the thermal performance is improved, and the emissions are reduced (Yilmaz, 2019).

4 CONCLUSION

In this sense, the results obtained demonstrate that photobioreactors have the potential for CO_2 capture and parallel production of substances that have the potential to improve the energy performance of combustion systems. Besides, process integration showed that photobioreactors could play a vital role in the sustainability of resilient fossil-based industrial processes since GHGs emissions could be substantially minimized.

Brazilian Journal of Development

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